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(54) [Title of the Invention]

Temperature-Compensated Quartz Crystal Oscillator

(57) [Abstract]

[Purpose] To provide a small-size crystal oscillator wherein frequency deviation does not exceed a tolerance

[Configuration] A crystal oscillator in which a temperature sensor 50 is provided near a crystal oscillator 55, including an AT-cut crystal resonator 11, wherein detected temperature is converted into digital temperature data by a temperature encoding circuit 51, and a correction signal based on the temperature data is sent to a V-C conversion circuit 56 to correct the frequency deviation of the crystal resonator 11, characterized in that an input/output characteristic of the temperature-encoding-circuit 51 is provided in the form of a pseudocubic curve characteristic that the gradient is maximum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator 11 is maximum or provided in the form of a multiple-gradient linear line characteristic approximate to the above-mentioned cubic curve characteristic is used.

[Effect] When obtaining temperature data, the temperature can be divided into small segments in the area where the frequency change rate varies sharply and the sampling bit number can be decreased.

[Claims]

[Claim 1]

A temperature-compensated crystal oscillator comprising a crystal oscillation circuit including an AT-cut crystal resonator whose frequency deviation changes with temperature changes, a temperature sensor for detecting a temperature near said crystal resonator, a temperature encoding circuit for having an analog signal representing a detected temperature inputted and outputting digital temperature data corresponding to said inputted value, and an oscillation frequency correction means for guiding a correction signal based on said temperature data to said crystal oscillation circuit and correcting an oscillation frequency, wherein as an input/output characteristic of said temperature encoding circuit, a pseudocubic curve characteristic that its gradient is minimum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator is minimum and its gradient is maximum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator is maximum is used.

[Claim 2]

A temperature-compensated crystal oscillator according to Claim 1, wherein said input/output characteristic of the temperature encoding circuit is provided as a pseudocubic curve characteristic or a multiple-gradient linear line characteristic approximate to said pseudocubic curve characteristic.

[Detailed Description of the Invention]

[0001]

[Field of the Invention]

The present invention relates to a temperature-compensated crystal oscillator for use in cellular or onboard wireless phones, and more specifically a crystal resonator characterized by an analog/digital conversion means of temperature information.

[0002]

It is well known that an AT-cut crystal resonator has a frequency temperature characteristic in a cubic curve and exhibits high performance in a wide range of frequencies. Fig. 3 is a diagram showing a frequency deviation-temperature characteristic of AT-cut crystal resonators of this kind. Numbers 11 to 18 denote cases of AT-cut crystal resonators cut at different angles.

[0003]

Generally, a frequency deviation ($\Delta F/F_0$) of an AT-cut crystal resonator is expressed by equation (1).

[0004]

$$\Delta F/F_0 = A_0(T-25)^3+B_0(T-25) \text{ [ppm] } \ldots\ldots\ldots \quad (1)$$

where A_0 is a third-order coefficient that depends on variation in cut and its value is about 9 to 10 $\times 10^{-5}$, and B_0 is a linear coefficient that chiefly depends on the cut angle and its value is about -2 to -4.5 $\times 10^{-1}$. By the way, T stands for temperature [℃].

[0005]

Meanwhile, with cellular and onboard wireless phones, the tolerance for the frequency deviation ($\Delta F/F_0$) is very small and, in the example of Fig. 4, within ±0.5 [ppm] in a temperature

range of -35℃ to +85℃. Therefore, the crystal resonators with characteristics shown in Fig. 3 are all outside the tolerance range. In the above-mentioned usage, a generally practiced method is that a temperature-compensated crystal oscillator is formed by providing a temperature compensation circuit in an oscillation circuit which includes an AT-cut crystal resonator and is controlled so that the fluctuations in the frequency deviation are within the tolerance.

[0006]

Fig. 5 is a block diagram of a conventional temperature-compensated crystal oscillator, in which number 50 denotes a temperature sensor, 51 denotes a temperature encoding circuit, 52 denotes a correction signal generating circuit, 53 denotes a data setting circuit, 54 denotes a LPF (low pass filter) built-in digital/analog conversion circuit (hereafter referred to as a D/A conversion circuit, and 55 denotes a crystal oscillation circuit.

[0007]

The crystal oscillation circuit 55 includes a specific AT-cut crystal resonator 11 having the characteristic shown in Fig. 3, a voltage-capacitance conversion circuit (hereafter referred to as V-C conversion circuit), such as a varactor diode, and an output circuit 57 serving as an interface between an oscillation portion circuit and an external circuit. Number 58 denotes a sequencer portion, and 59 denotes a CR oscillator. Note that the CR oscillator 59 may sometimes be replaced by dividing output in Fig. 5.

[0008]

Next, the operation of the crystal oscillator configured as described is explained briefly as follows.

[0009]

In the V-C conversion circuit 56, if the input reverse voltage v to the baractor diode (Cv) is at about the center v_0 of a variable range of the D/A conversion circuit 54 and an equivalent capacitance corresponding to this voltage vo is denoted as Cv_0, an oscillator output frequency Fo at this time is expressed by equation (2).

[0010]

$$F_o \fallingdotseq F_3\{1+\frac{1}{2r(1+\frac{C_L}{C_o})}\} \quad \dots \text{ (2)}$$

Here,

$$C_L = \frac{C_K(C_A + C_{VO})}{C_K + C_A + C_{VO}}$$

[0011]

In equation (2), C_A is a parallel capacitance to adjust the sensitivity of the varactor diode (Cv), and its temperature coefficient is set at "0" (unsusceptible to temperature changes) for convenience sake. Ck is an input terminal capacitance of the output circuit 57 and its temperature coefficient is similarly set at "0." Further, Fs, Co and r are equivalent constants of the crystal resonator 11 and respectively denote a series resonator frequency, a parallel capacitance and a capacitance ratio (Co/C_L).

[0012]

Consider here a case where the environmental temperature

of a temperature-compensated crystal oscillator has risen from -25℃ to +62℃, for example. In this case, according to Fig. 3, the frequency deviation of the crystal resonator 11 is -10.5[ppm]. The temperature sensor 50 detects the temperature at this time and sends it to the temperature encoding circuit 51.

[0013]

The temperature encoding circuit 51 is a circuit for having an analog signal representing a detected temperature inputted and outputting digital temperature data corresponding to the inputted value. To be more specific, the temperature encoding circuit 51 includes a temperature/voltage conversion portion for converting a detected temperature into an (analog) voltage, an amplifier for amplifying an after-conversion voltage to a predetermined level, and an analog/digital (A/D) conversion portion for outputting a digital signal corresponding to the voltage value. As shown in Fig. 6, the A/D conversion portion has a proportional characteristic between digital output (temperature data Da) 62 and analog input (detected temperature T) 61 and sends temperature data Da, which corresponds to the detected temperature of 62 ℃, to the compensation signal generating circuit 52.

[0014]

The correction signal generating circuit 52 includes a storage device, such as an E^2-PROM (electrically erasable ROM), a flash ROM, or a one-time ROM. Digital temperature data Da serving as address data and digital correction signals Dv1 (described later) corresponding to the temperature data are

written by a data setting circuit 53. This correction signal generating circuit 52 reads correction signals Dv1 from addresses corresponding to temperature data Da of 62℃ and sends signals to the D/A conversion circuit 54.

[0015]

The D/A conversion circuit 54 converts the correction signal Dv1 into analog form and lets the signal pass the LPF and sends it to the V-C conversion circuit 56 where a reverse voltage v1 corresponding to the correction signal Dv1 is applied to the varactor diode.

[0016]

As the reverse voltage across the varactor diode increases from v0 to v1, its equivalent capacitance decreases according to the reverse voltage. The equivalent capacitance at this time is designated as Cv1. Referring to the equation (2) shown above, it is understood that as the equivalent capacitance (Cv_0) of the varactor diode decreases, the oscillator output frequency (F_0) becomes higher. In the above-mentioned example, for instance, if the oscillator output frequency is designated as F1, it follows that the frequency deviation has been as:

[0017]

$$\Delta F/F_0 = (F_1 - F_0)/F_0 = -10.5\ [\mathrm{ppm}]$$

Therefore, if the equivalent capacitance Cv1 of the varactor diode is adjusted so that this oscillator output frequency F_1 limitlessly approaches F_0, temperature compensation is achieved.

[0018]

The equivalent capacitance Cv1 at this time is obtained

by equation (4):

[0019]

$$C_{V1} = \frac{C_K C_L' - (C_K - C_L') C_A}{C_K - C_L'} \quad \cdots (4)$$

Here,

$$C_{L'} = \frac{C_L + \beta C_o}{1 - \beta}$$

$$\beta = \alpha \bullet \frac{\Delta F}{F_o}$$

$$\alpha = 2r\left(1 + \frac{C_L}{C_o}\right)$$

[0020]

What becomes source data of the reverse voltage v1 when the equivalent capacitance is Cv1 is the correction signal Dv1 described above.

[0021]

The above-mentioned series of motions are controlled by a sequencer portion 58. In other words, on the basis of a clock signal output from the CR oscillator 59, the sequencer portion 58 generates new clock signals to decide timing of temperature data output from the temperature encoding circuit 51 to the correction signal generating circuit 52 and timing of data output from the correction signal generating circuit 52 to the D/A conversion circuit 54.

[0022]

[Problem to be solved by the Invention]

Meanwhile, in the crystal oscillator configured as

described, to perform appropriate temperature compensation, a prerequisite is that the following conditions should be satisfied.

[0023]

(1) The temperature sensor 50 should accurately detect the temperature of the crystal oscillation circuit 55 without delay.

[0024]

(2) The temperature encoding circuit 51 should perform A/D conversion with sufficiently small quantizing errors. For example, for quantization with accuracy of 0.125[℃/dig (a dig means a unit digital amount, which equally applies to the following description) or better, a data length of at least 10 bits is required.

[0025]

The correction signal output from the correction signal generating circuit 52 should have a sufficient data length.

[0026]

(4) The D/A conversion circuit 54 should perform conversion with small errors.

[0027]

(5) The sequencer portion 58 should have processing timing which takes into account the ambient temperature change rate and a jitter.

[0028]

To meet all those conditions, each part must be configured to be compatible with the above-mentioned data length (bit number), and a separate correction circuit, for example, is

required. Therefore, the oscillator size becomes large and its cost become high. With onboard wireless equipment, what is on demand is at least to downsize the crystal oscillator, and to this end, it is necessary to limit the data length of the temperature encoding circuit 51 to about 8 bits and, in conjunction with this, it is also necessary to take measures such as reducing the storage device capacity of the correction signal generating circuit 52. Under such a condition, however, there arise two problems as follows.

[0029]

One problem is that a lowering quantization accuracy and sudden changes in frequency are inevitable. If a temperature range of -35℃~+85℃ is to be covered when the data length of the temperature encoding circuit 51 is 8 bits, each temperature data Da becomes 0.5[℃/dig]. In this case, the change rate of frequency deviation obtainable by the equation (1), briefly, the frequency change rate becomes as shown in equation (5) below. For example, with a crystal oscillator 14 shown in Fig. 3, the frequency change rate of frequency deviation is expressed by a second order curve in a downward convex shape as shown in Fig. 7.

[0030]

$$\frac{\partial(\frac{\Delta F}{F_0})}{\partial T} = 3A_0(T-25)^2 + B_0 \qquad \dots \ (5)$$

[0031]

On the other hand, considering cases of all those crystal resonators 11 to 18, the one whose frequency change rate is

maximum is the crystal resonator 18, and in this case, the values at -35℃ and 85℃ are obtained as follows.

[0032]

$$\frac{\Delta F}{F_o} = 1.2[\mathrm{ppm}/℃] \times 0.5[℃/\mathrm{dig}] = 0.6[\mathrm{ppm}/\mathrm{dig}] \quad \ldots (6)$$

[0033]

In this case, a change for 1dig is expressed by equation (6), and this value is obviously larger than the target deviation maximum value of 0.5[ppm].

[0034]

$$\frac{\partial\left(\frac{\Delta F}{F_0}\right)}{\partial T} = 1.2\ [\mathrm{ppm}/℃]$$

[0035]

Further, in a worst case where there is a temperature change close to 2 dig, this value is 1.2[ppm], which widely exceeds the target deviation width.

[0036]

Another problem is jitter. If the data length is 8 bits, as described earlier, because a temperature step is 0.5[℃/dig], as is obvious from equation (6), a jitter of 0.6[ppm] at largest occurs. In this case, even if the effect of the LPF in the D/A conversion circuit 54 is the same as in the case of 10 bits, the amount of jitter becomes four times larger (2^2) due to the reduction by 2 bits; therefore, also in this case, the target deviation width is exceeded.

[0037]

The present invention has been made under such a background

and has its object to provide a temperature-compensated crystal oscillator capable of appropriately compensate for frequency fluctuations owing to temperature changes.

[0038]

[Means for Solving the Problem]

A temperature-compensated crystal oscillator comprising a crystal oscillation circuit including an AT-cut crystal resonator whose frequency deviation changes with temperature changes, a temperature sensor for detecting a temperature near the crystal resonator, a temperature encoding circuit for having an analog signal representing a detected temperature inputted and outputting digital temperature data corresponding to the inputted value, and an oscillation frequency correction means for guiding a correction signal based on the temperature data to the crystal oscillation circuit and correcting an oscillation frequency, wherein as an input/output characteristic of the temperature encoding circuit, a pseudocubic curve characteristic that its gradient is minimum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator 11 is minimum and its gradient is maximum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator 11 is maximum is used.

[0039]

The input/output characteristic of the temperature encoding circuit may be provided as a pseudocubic curve characteristic or a multiple-gradient linear line characteristic approximate to the pseudocubic curve

characteristic.

[0040]

[Function]

As the input/output characteristic of the temperature encoding circuit is configured in a pseudocubic curve, temperature data is output which is conforming to the frequency temperature characteristic of an AT-cut crystal resonator. More specifically, in a region where the gradient of the pseudocubic cubic curve is large, the temperature for 1dig becomes small, so that different temperature data is output according to slight temperature changes. Therefore, in this region, as in a case where the bit number of the A/D converter portion is large, the oscillation frequency is corrected frequently.

[0041]

On the other hand, in the region where the frequency change rate per unit temperature is minimum, if the temperature for 1dig is made large, there is practically no problem.

[0042]

Note that the above function is the same even if a linear characteristic with a plurality of gradients, which is approximate to a pseudocubic curve characteristic, used.

[0043]

[Embodiment]

Embodiments of the present invention will be described with reference to the accompanying drawings. By the way, the temperature-compensated crystal oscillator according to the present invention, having the same component parts as in a

conventional product, is explained by using the same names and codes shown in Fig. 5 as they stand.

[0044]

In this embodiment, the input/output characteristic of the temperature encoding circuit 51 (A/D converter) has been improved in a conventional temperature-compensated crystal oscillator.

[0045]

Fig. 1 is an input/output characteristic diagram by this embodiment, in which the horizontal axis indicates detected temperature [℃] and the vertical axis indicates temperature data. Fig. 1 shows an example of an average AT-cut crystal resonator 14 having a characteristic shown in Fig. 3. In other words, referring to Fig. 3, the frequency change rate per unit temperature of the crystal resonator 14 is minimum at -10℃ and 60℃.

[0046]

$$\frac{\partial(\Delta F/F_0)}{\partial T}$$

[0047]

On the other hand, the frequency change rate per unit is maximum when the temperature is in the vicinity of -35℃ and 85℃.

[0048]

$$\frac{\partial(\Delta F/F_0)}{\partial T}$$

[0049]

In addition, the changes of the frequency deviation ($\Delta F/F_0$)

conforms to a cubic curve as is obvious from the equation (1).

[0050]

The input/output characteristic of the temperature encoding circuit 51 is provided as a pseudocubic curve characteristic that its gradient is maximum at -35℃ and 85℃ and that the gradient is minimum when the temperature is in the vicinity of -10℃ and 60℃. To be more concrete, the temperature T1 at an inflection point of the cubic curve is:

[0051]

$$T_1 - \sqrt{\frac{-B_0}{3A_0}} + 25 \quad [℃]$$

[0052]

In this case, in a range from −T1 to T1, more specifically, from -10 to 60 in the example of Fig. 1, one line segment is mapped to a line through the origin, with the coordinates of the line one the negative side is added with a minus sign, and beyond this range, an ordinary cubic curve is coupled to the mapped line.

[0053]

For example, in Fig. 1, when detected values of temperature T on the horizontal axis are -35℃ and 85℃, if temperature data on the vertical axis Y at these temperatures are designated as K and −K, Y is expressed in a curve represented by a functional equation (8) in the range of -10℃ ≦ T ≦ 60℃.

[0054]

$$Y = \frac{K}{16.37}\{-9.8\times10^{-5}(T-25)^3 - 0.36(T-25)\} \quad \ldots \quad (8)$$

[0055]

Further, in the range of 60℃ ≦ T ≦ 85℃, Y is expressed in a curve represented by a functional equation (9).

[0056]

$$Y = \frac{K}{16.37}\{9.8 \times 10^{-5}(T-25)^3 - 0.36(T-25) + 16.80\} \quad \dots (9)$$

[0057]

Further, in the range of -35℃ ≦ T ≦ -10℃, Y is expressed in a curve represented by a functional equation (10).

[0058]

$$Y = \frac{K}{16.37}\{9.8 \times 10^{-5}(T-25)^3 - 0.36(T-25) - 16.80\} \quad \dots (10)$$

[0059]

According to the input/output characteristic set as described, in the range of -35℃ and 85℃ where the gradient of the curve is large in Fig. 1, the temperature for 1dig is small, and different temperature data Da is output even by small temperature changes. This acts as if the sampling bit number is increased. For example, if the gradient in those temperature ranges is 1.5 times that in the conventional proportional linear characteristic, the temperature for 1dig is 0.33℃ and the frequency deviation corresponding to equation (6) is 0.4[ppm]. Therefore, even if the A/D converter performs 8-bit quantization, there is no longer any chance that the above value the maximum value of target deviation is exceeded and thus the problems of quantization accuracy and jitter have been solved.

[0060]

On the other hand, in the region where the gradient of the

curve in Fig. 1 is small, though the temperature for 1dig becomes large, because the frequency change rate in this temperature range is small, there is practically no problem and temperature data Da is output with frequency in accordance with the change rate.

[0061]

A pseudocubic curve characteristic such as this can be realized easily by generating output addresses Y of the A/D converter corresponding to detected temperature T in a manner to satisfy the equations (8) to (10).

[0062]

Incidentally, the above-mentioned input/output characteristic may be provided as a linear line characteristic having a plurality of gradients, which is approximate to the pseudocubic curve characteristic. Fig. 2 illustrates an input/output characteristic in this case, and shows an embodiment having conditions close to a pseudocubic curve formed by the following linear functions in respective temperature ranges formed by dividing a range from -35℃ to 85℃, for example, into five temperature ranges.

[0063]

$$Y = K(T-5)/40 \quad \ldots\ldots\ldots \quad (11)$$

$$(-35℃ \leqq T \leqq -25℃)$$

[0064]

$$Y = K(T-65)/120 \quad \ldots\ldots\ldots\ldots \quad (12)$$

$$(-25℃ \leqq T \leqq 5℃)$$

[0065]

$$Y = K(T-25)/40 \quad \ldots\ldots\ldots\ldots \quad (13)$$

$$(5℃ \leqq T \leqq 45℃)$$

[0066]

$$Y = K(T+15)/120 \quad \ldots\ldots\ldots\ldots \quad (14)$$

$$(45℃ \leqq T \leqq 75℃)$$

[0067]

$$Y = K(T-45)/40 \quad \ldots\ldots\ldots\ldots \quad (15)$$

$$(75℃ \leqq T \leqq 85℃)$$

According to the linear line characteristic as described above, almost the same effect as with a pseudocubic curve can be obtained. Moreover, it is possible to equally divide the output addresses Y of the A/D converter corresponding to detected temperatures T, and because their generation is easier than with the pseudocubic curve characteristic and attention has only to be paid to stability, this can become a more popular means.

[0068]

Note that the equations (11) to (15) are given to show an example, and by subdividing the temperature range, it is possible to approximate the linear characteristic closer to a pseudocubic curve characteristic.

[0069]

Figs. 1 and 2 show an example of an oscillation circuit 55 including an average AT-cut crystal resonator 14. However,

needless to say, this embodiment can be similarly applied to cases of other crystal resonators 11 to 13 and 15 to 18. In such a case, by calculating an inflection temperature T1 for each crystal resonator according to Fig. 3 and changing the constants (temperature condition) of the equations (8) to (15), a pseudocubic curve characteristic inherent to each crystal resonator can be obtained.

[0070]

[Effect of the Invention]

As has been described in detail, in a temperature-compensated crystal oscillator, an input/output characteristic of the temperature encoding circuit is provided in the form of a pseudocubic curve characteristic that its gradient is minimum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator is minimum and its gradient is maximum in the vicinity of a temperature at which the frequency change rate per unit temperature of the crystal resonator is maximum. Therefore, in the region where the frequency deviation change rate is large, the corresponding temperatures can be subdivided, which provides an effect as if the sampling bit number is increased. As a result, the bit number and data length of the data processing circuit, including the temperature encoding circuit, can be decreased, thereby saving the storage capacity of the storage device, so that the crystal oscillator can be reduced in size and price.

[0071]

By using a plurality of linear characteristics with

different gradients, which together approach the above-mentioned cubic curve characteristic, it becomes possible to form a characteristic fairly easily, thus greatly reducing production cost.

[0072]

As has been described, according to the present invention, even if AT-cut crystal resonators are used, which have different frequency-temperature characteristics caused by a shift or variation of the cut angle, temperature compensation in accordance with each characteristic can be performed easily; therefore, it is possible to provide a small-size temperature compensated crystal oscillator which can made effective use of the crystal resonator and which can be used in severe usage within permissible limits of frequency deviation.

[Brief Description of the Drawings]

Fig. 1 is an input/output characteristic (pseudocubic curve characteristic diagram) of a temperature encoding circuit according to an embodiment of the present invention;

Fig. 2 is an input/output (linear characteristic diagram) of a temperature encoding circuit according another embodiment of the present invention;

Fig. 3 is a frequency deviation-temperature characteristic diagram of an ordinary AT-cut crystal resonator;

Fig. 4 is a diagram for explaining permissible frequency deviations of cellular phones, and so on;

Fig. 5 is a block diagram of a conventional temperature compensated crystal oscillator to which the present invention is applied;

Fig. 6 is an input/output characteristic diagram (proportional straight line characteristic diagram) of a conventional temperature encoding circuit; and

Fig. 7 is a frequency deviation change rate in an average AT-cut crystal resonator.

[Description of Codes]

11-18 ... AT-cut crystal resonators

50 ... Temperature sensor

51 ... Temperature encoding circuit

52 ... Correction value signal generating circuit

53 ... Data setting circuit

54 ... D/A conversion circuit

55 ... Crystal oscillation circuit

56 ... V-C conversion circuit

57 ... Oscillation circuit and output circuit

58 ... Sequencer circuit

59 ... CR oscillator

FIG. 1

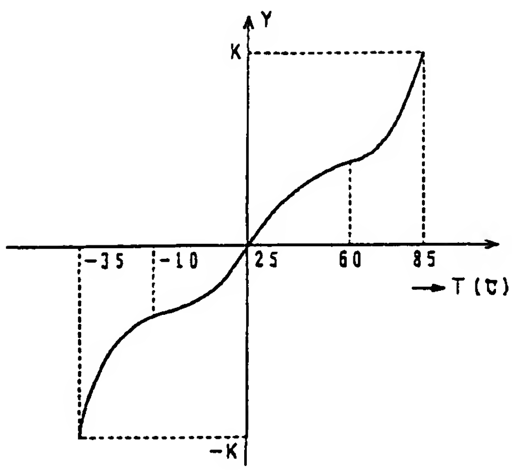


FIG. 2

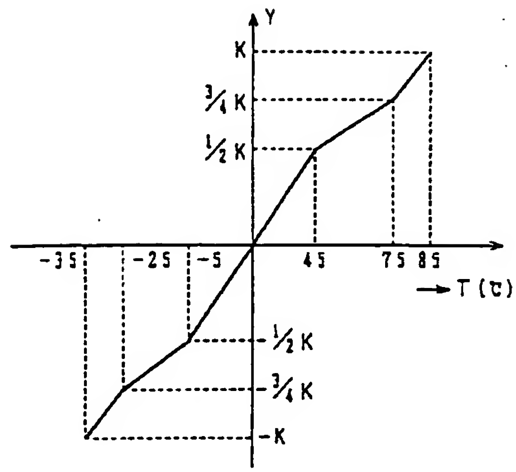


FIG. 3

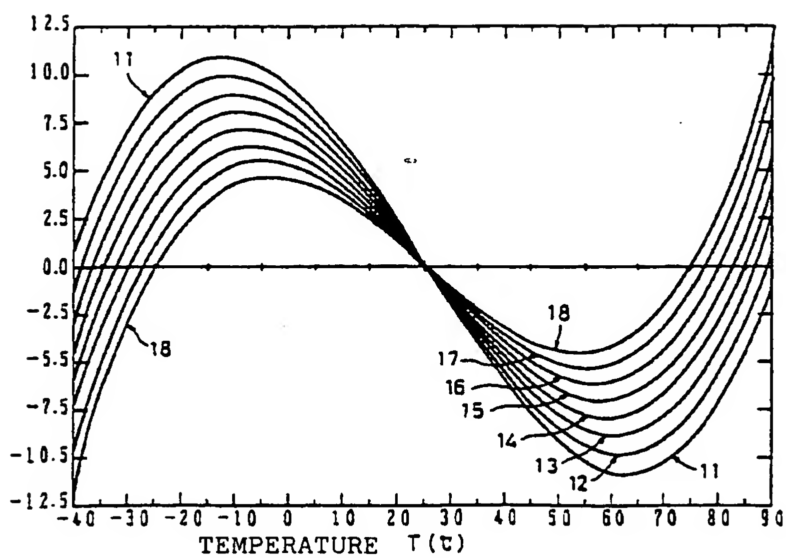


FIG. 4

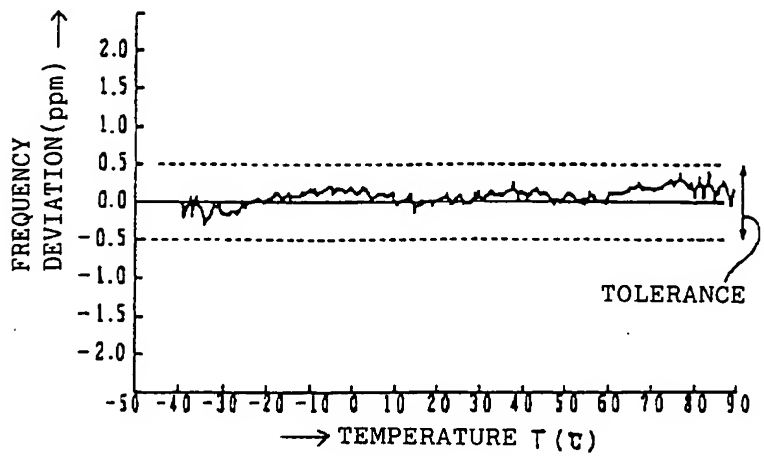

FREQUENCY DEVIATION (ppm)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
TOLERANCE
-50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90
TEMPERATURE T (℃)

FIG. 5

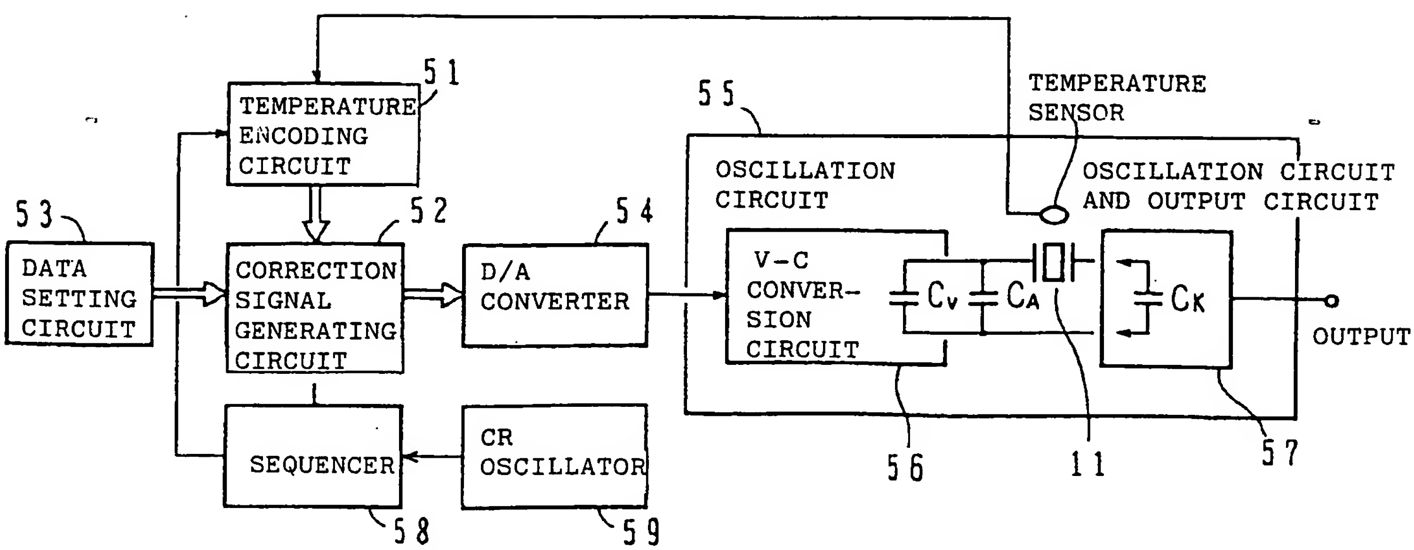
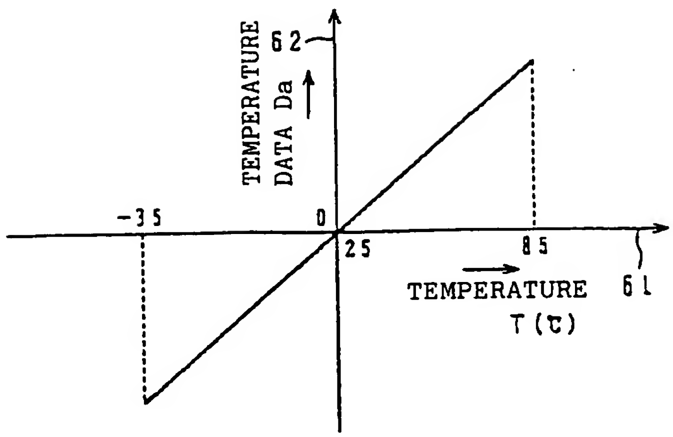

TEMPERATURE ENCODING CIRCUIT
51
55
TEMPERATURE SENSOR
OSCILLATION CIRCUIT
OSCILLATION CIRCUIT AND OUTPUT CIRCUIT
53
52
54
DATA SETTING CIRCUIT
CORRECTION SIGNAL GENERATING CIRCUIT
D/A CONVERTER
V-C CONVER-SION CIRCUIT
Cv
CA
CK
OUTPUT
SEQUENCER
CR OSCILLATOR
56
11
57
58
59

FIG. 6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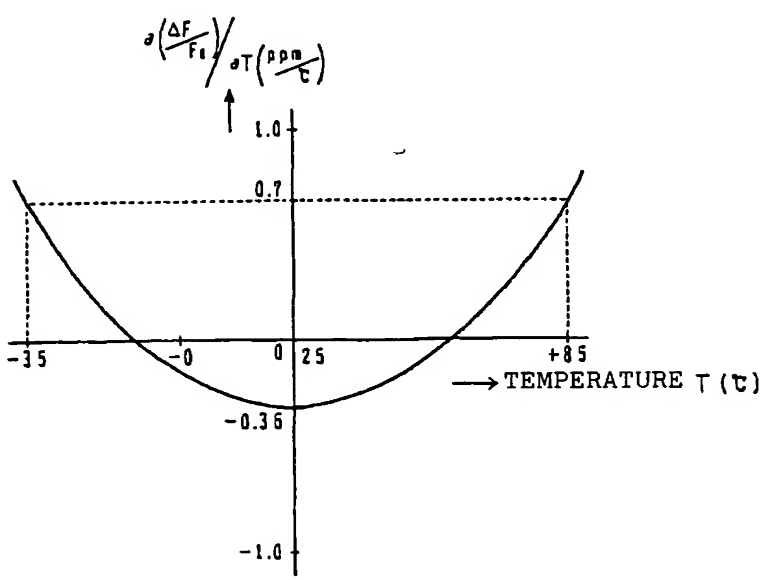
62
-35
0
25
85
TEMPERATURE
T (℃)
61

FIG. 7


1.0
0.7
-35
-0
0
25
+85
TEMPERATURE T (℃)
-0.36
-1.0